Visualization and Analytics Requirements of the Fusion SciDACS

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With input from D. Batchelor (ORNL), S. Klasky (ORNL), S. Jardin (PPPL)

Outline

- Brief overview of the computational modeling of fusion plasmas
  - Some needed jargon explained
    - Especially the zoology of the fusion computational ecology
    - Fusion has 6 SciDACs
- What are the analytics/visualization requirements of these groups
  - Biased towards my background, of course (MHD computations)

What Does It Take To Achieve A Fusion Reactor?

- First some definitions:

  n: number density (number of particles per volume)

  T: temperature (either of ions or electrons)

  τ_E: energy confinement time scale

- Balancing losses with fusion generation yields Lawson criterion:

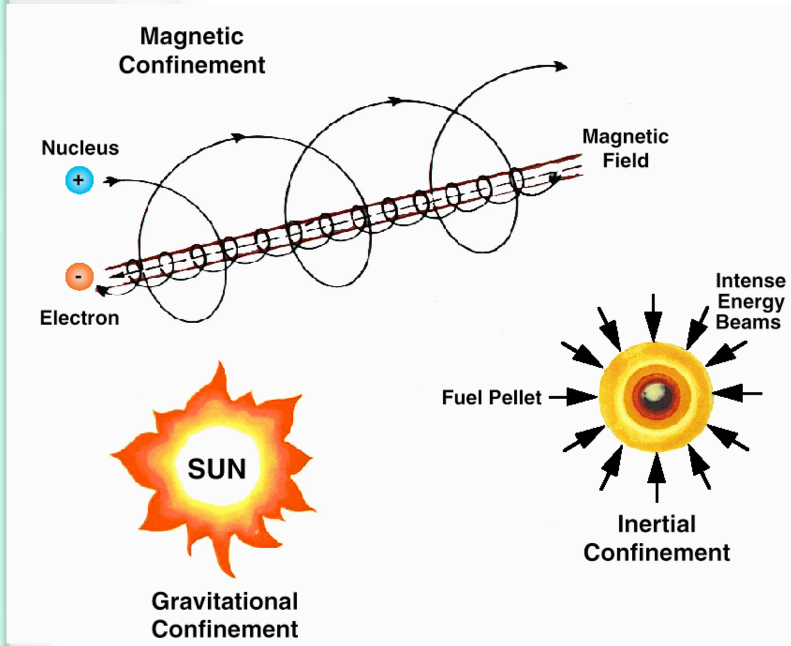
$$nT\tau_E > 10^{21}$$

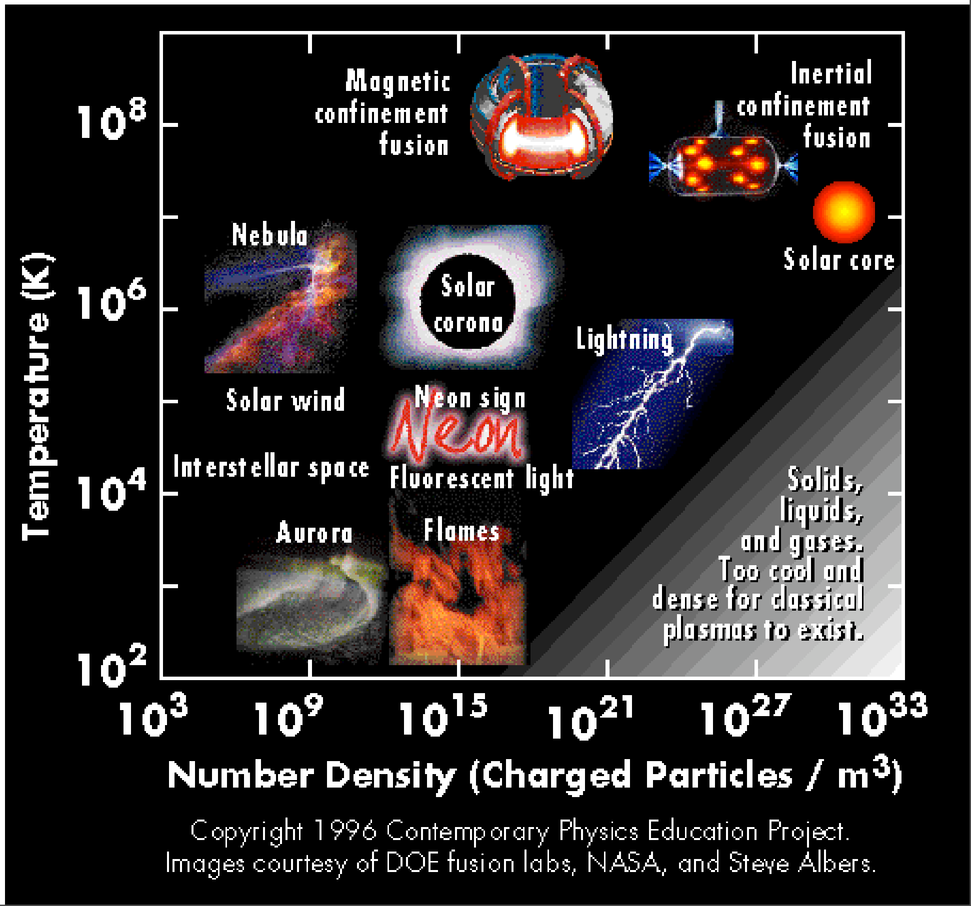
Need them to hold them long enough

Need them to be hot

Need lots of particles in device

Magnetic Confinement Fusion Uses Magnetic Field to Shield Hot Plasma From Material Wall





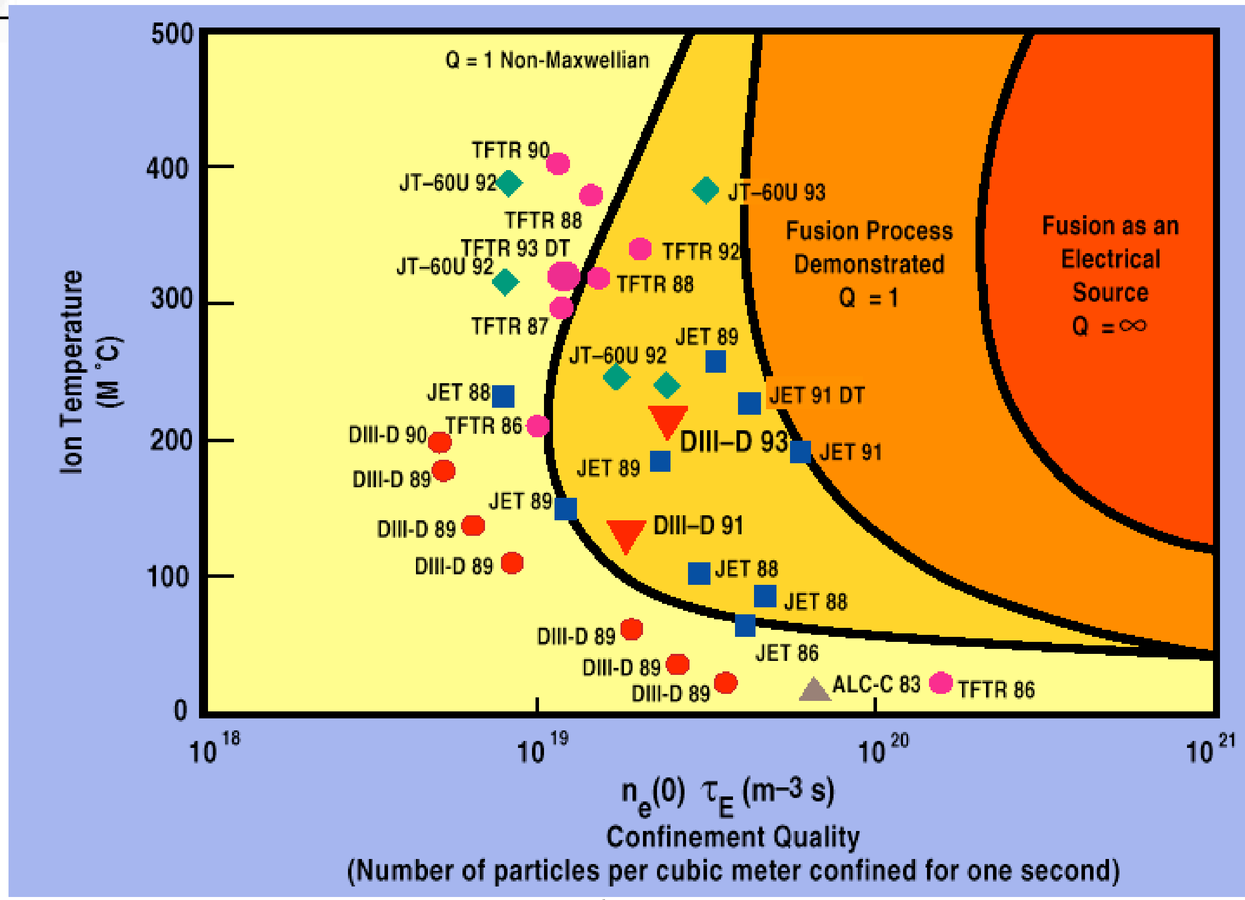
Parallel to magnetic field line

⇒Very fast

Perpendicular

⇒Slow

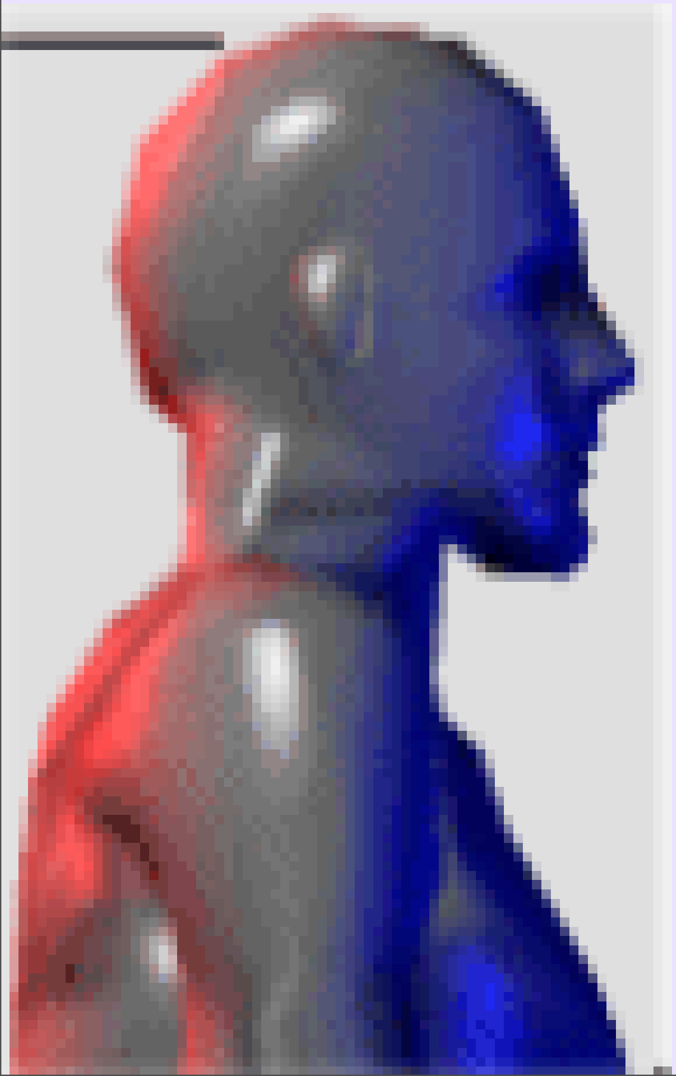
Tokamak Performance Closest to Reactor Conditions



$$Q = \frac{P_{fusion}}{P_{heating}} \Rightarrow \begin{cases} = 1 \rightarrow \text{break even} \\ > 20 \rightarrow \text{energy feasible} \\ \infty \rightarrow \text{ignition} \end{cases}$$

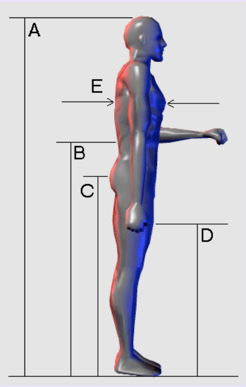
Progress in fusion ***1960***

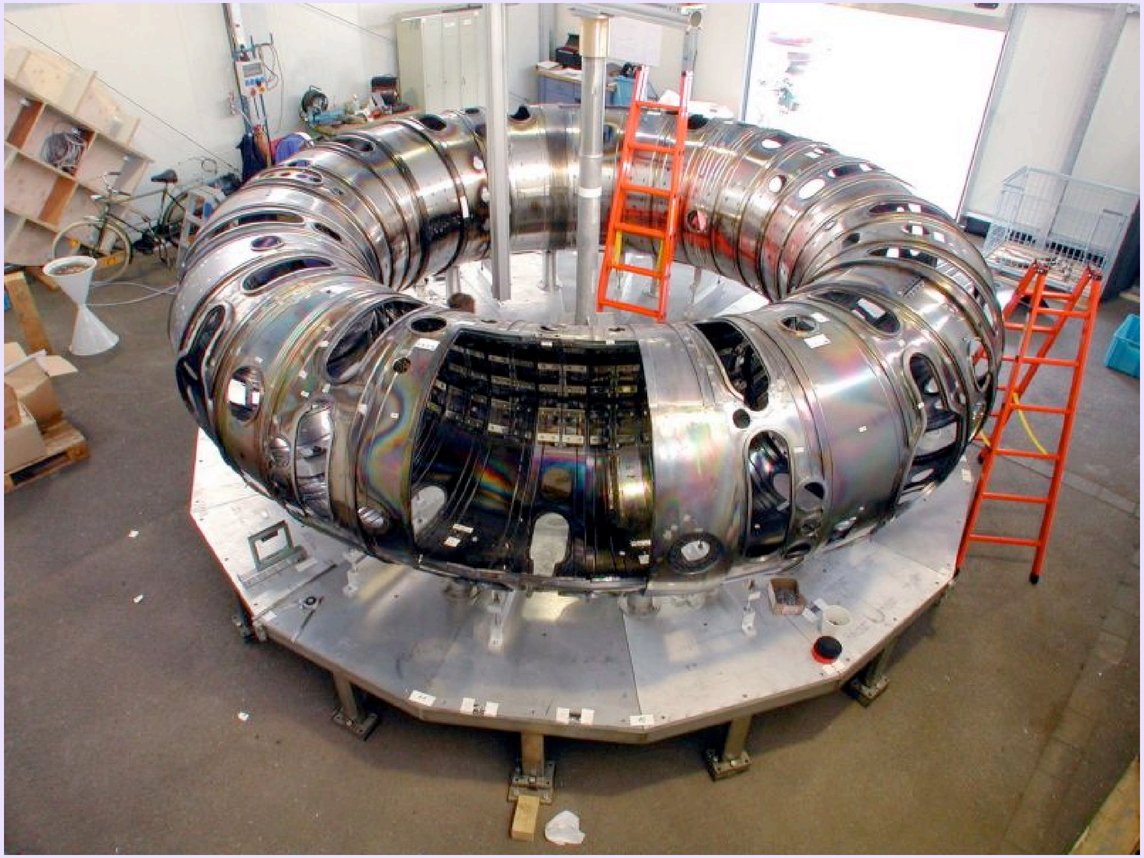
Progress in fusion **1970**



Progress in fusion **1980**

τ_E~20 msec



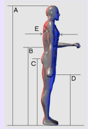


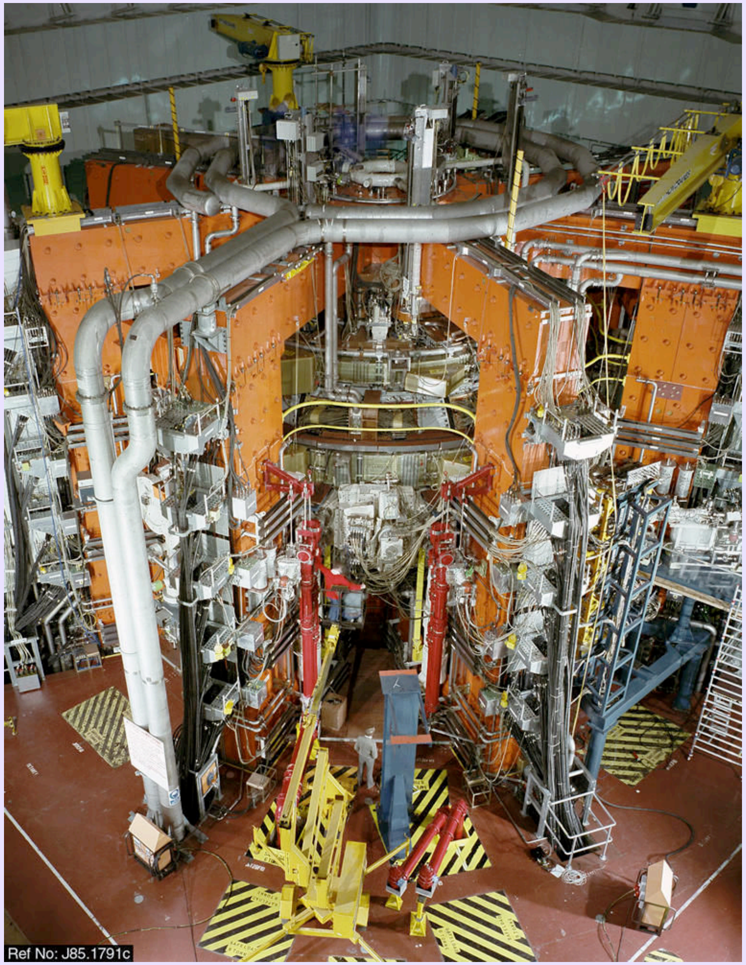
Progress in fusion **1990**

JET

$\tau_E \sim 1$ sec

Plasma duration: 10 sec





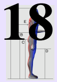
Progress in fusion **2010**

ITER

designated number one priority

for new scientific facilities

- **Fusion power ~ 500MW**
- **I_{plasma} = 15 MA, B_0 = 5 Tesla**
  T ~ 10 keV, τ_E ~ 4 sec
- **Large – 30m tall, 20kTons**
- **Expensive > $5B+**
- **Project staffing, administrative organization, environmental impact assessment, design**
- **First burning plasmas ~2018**



Latest news ***http://www.iter.org***

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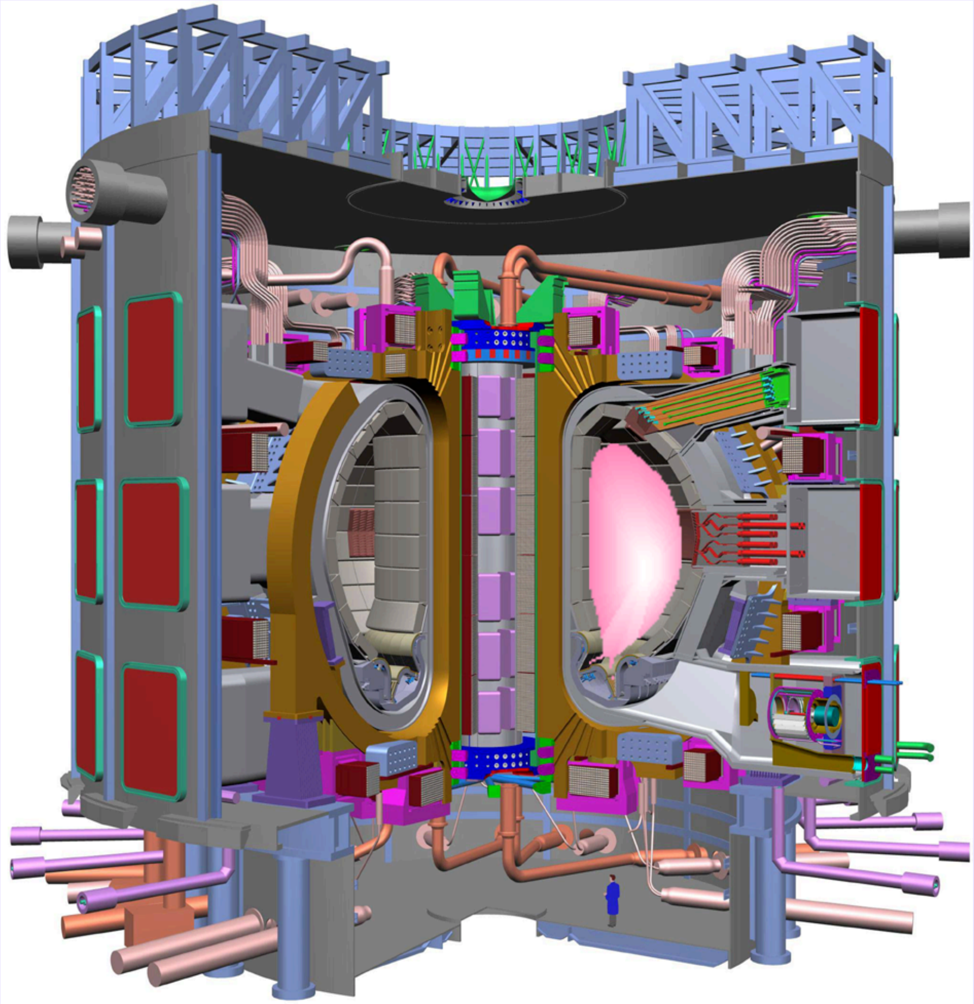

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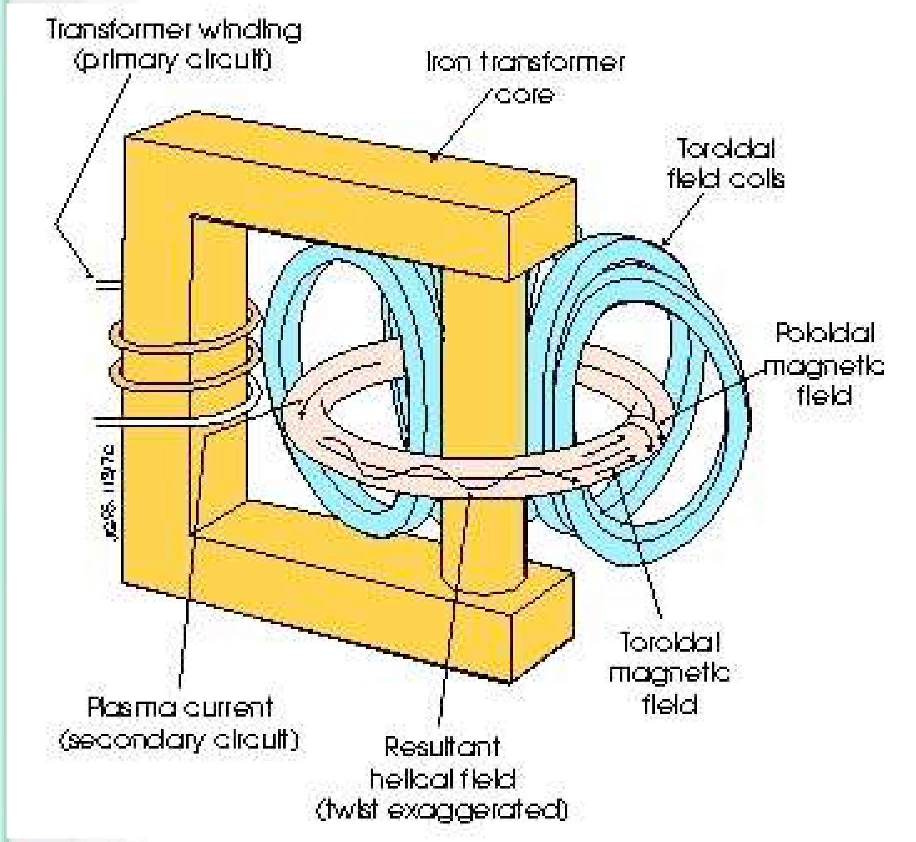
Why is the tokamak so successful?

Toroidal confinement requires both toroidal and poloidal magnetic fields



Tokamak:

Large external magnets for toroidal field

Plasma current generates poloidal magnetic field

Good:

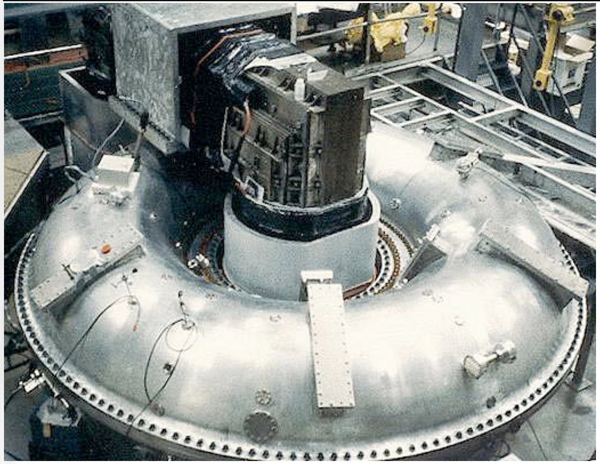
Helical field is mostly symmetric

Bad:

Toroidal current can drive instabilities.

External magnets are expensive

Alternatives illustrate problems of

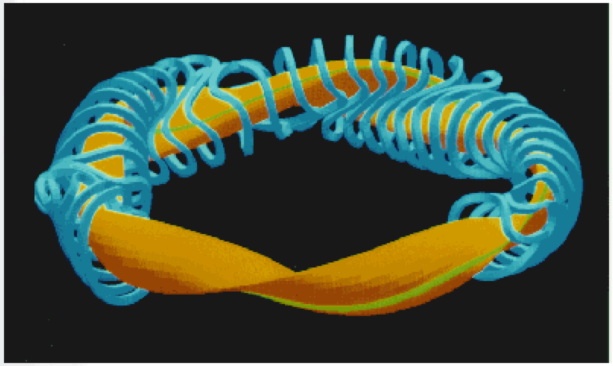


Reverse Field Pinch

~ a tokamak w/o toroidal magnetic field

Bad:

Without external magnetic field, plasma current leads to lots of instabilities which gives stochastic fields



Stellarator

Poloidal field produced by external coils

Bad:

Getting good confining field is difficult.

How Can We Make Tokamak More Successful? (How Can We Make It *Economical?)*

"Knobs" that experimentalists have in control room:

- Sources
  - Temperature, Current, Momentum: Neutral beams (NBI), radiofrequency (RF), Ohmic
  - Density: NBI, gas puff, pellet
  - Impurity: Gas puffing, wall conditioning, pumping
- Shape of plasma (using poloidal field (PF) coils)
- …

Parameter space for tokamak operation is very large!

Room for computation to make an impact

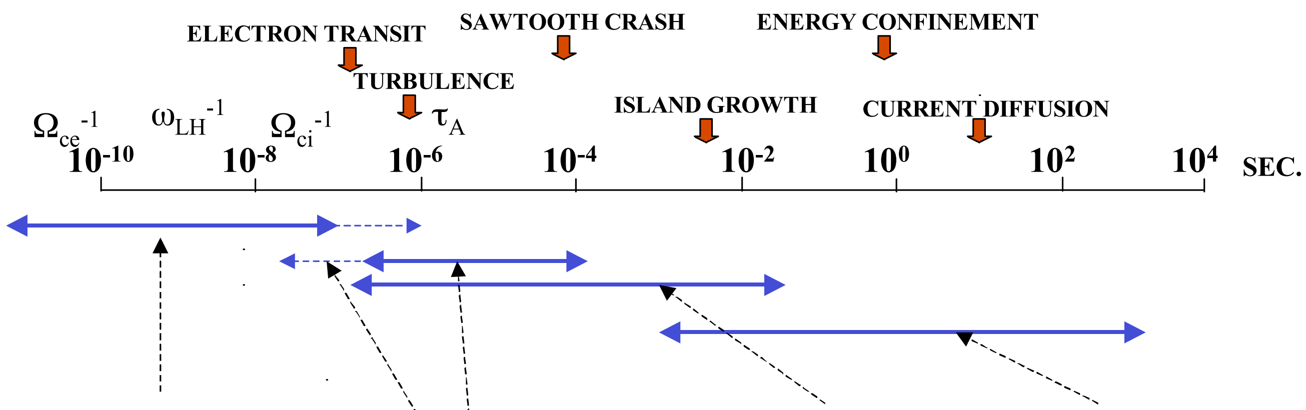
How Do We Computationally Model Tokamak Plasmas?

- Extreme range of time scales
  wall equilibration/electron cyclotron $O(10^{14})$
- Extreme range of spatial scales
  machine radius/electron gyroradius $O(10^{4})$
- Extreme anisotropy
  Particles move much faster parallel to magnetic field than perpendicular magnetic fields
- High dimensionality
  Only equation that plasma physicists trust is 7D $\rightarrow$ f(x, v, t), described by non-linear Boltzman equation for each species

$$\frac{\partial f}{\partial t} + \mathrm{v} \times \nabla f + \tfrac{q}{m}\left[E + \mathrm{v} \times B\right] \times \nabla_{\mathrm{v}} f = C(f)$$

… with lots of approximations.

Typical Time Scales in a next step experiment
with B = 10 T, R = 2 m, $n_e = 10^{14}$ cm^{-3}, T = 10 keV



Single frequency and prescribed plasma background RF Codes wave-heating and current-drive	Neglect displacement current, average over gyroangle, (some) with electrons Gyrokinetics Codes turbulent transport	Neglect displacement current, integrate over velocity space, neglect electron inertia Extended MHD Codes device scale stability	Neglect displacement current, integrate over velocity space, average over surfaces, neglect ion & electron inertia Transport Codes discharge time-scale
7D	5D	3D	2D

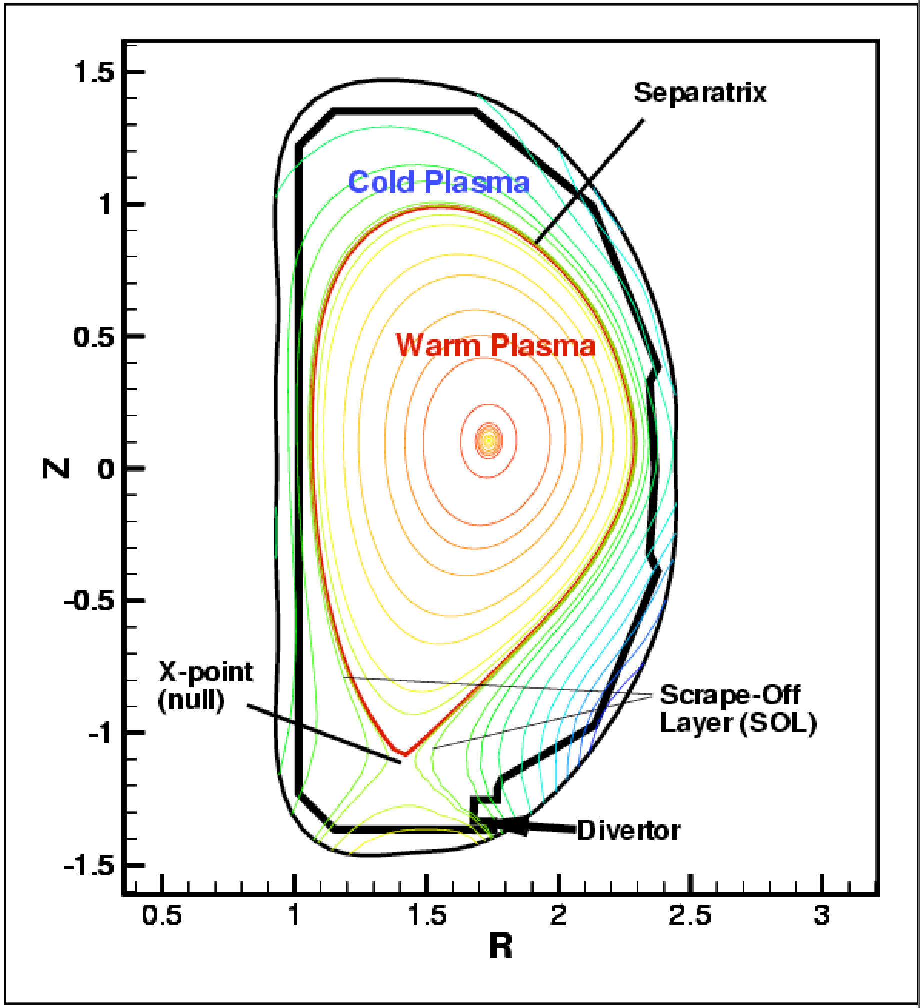
Jardin

Edge Region Fundamentally Different Than Core Plasma

- Edge = open-field line region (plus a little bit of closed-field line region)

- Balance of parallel transport to wall and perpendicular transport from core

- Lots of really hard physics:
  - Plasma-wall interactions
  - Neutral transport
  - Atomic Physics
  - Geometry
  - Narrow gradients

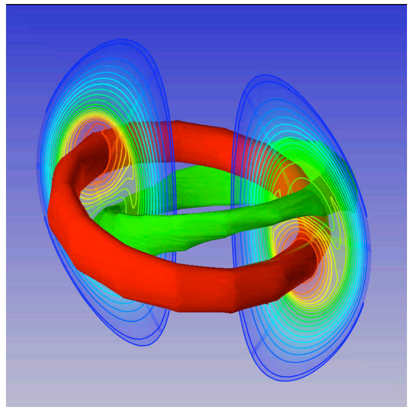


SciDAC and other projects addressing separate phenomena and time scales

Center for Extended MHD Modeling

PI: S. Jardin (PPPL)

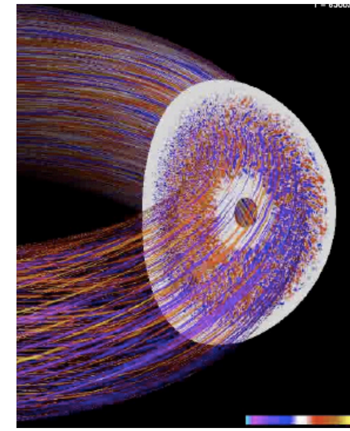
- M3D code
- NIMROD



Gyrokinetic Particle Simulation Center

PI: W. Lee (PPPL)

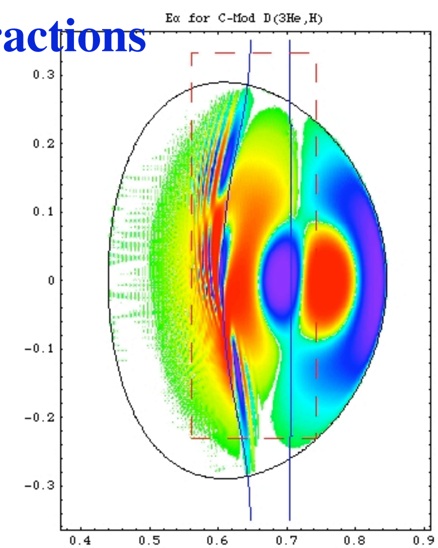
- GTC code
- Note: GYRO



Center for Simulation of Wave-Plasma Interactions

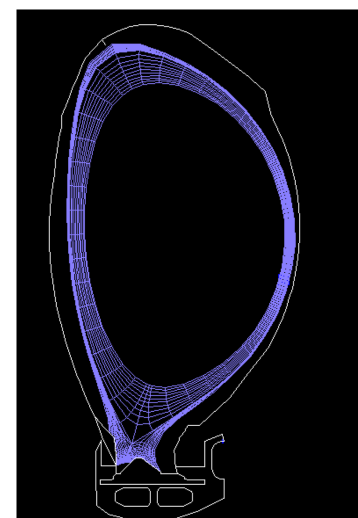
PI: P. Bonoli

- AORSA code
- TORIC
- CQL3D
- ORBITRF
- DELTA5D

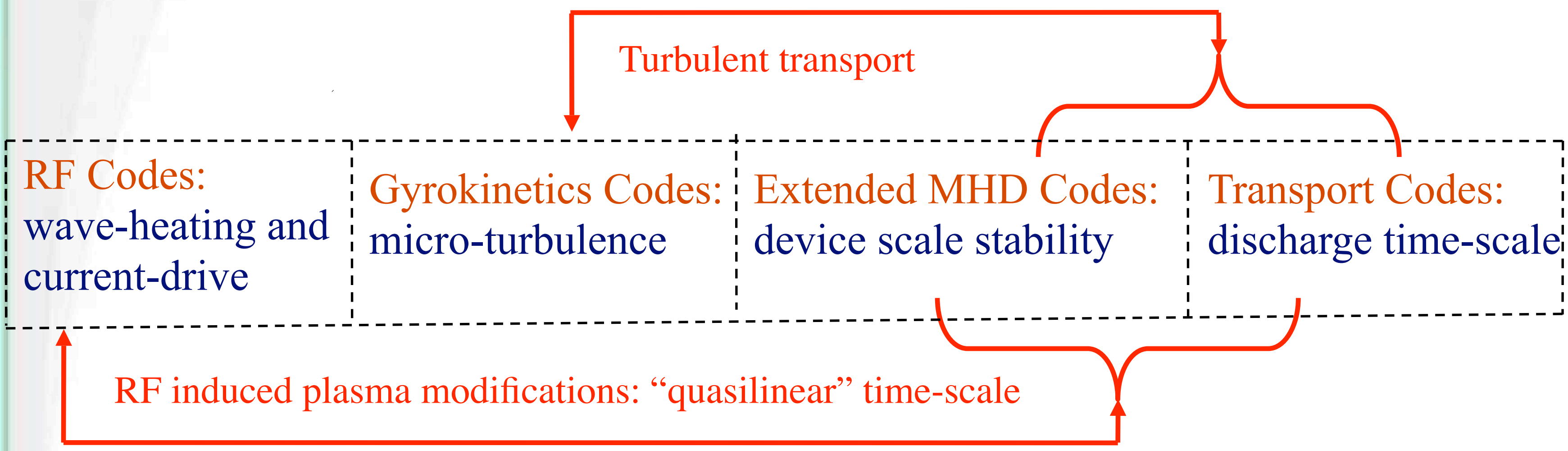


Edge Simulation Projects (OFES-funded)

- XGC code
- TEMPEST



Integrated Simulation – even when the time scales are separated they can interact



- Unlike climate model components (atmosphere, land-mass, ocean, sea ice) which have a separating boundary, coupled fusion process can occur at the same time, in the same place, in the same chunk of plasma
- Our ultimate goal is to couple all of the relevant processes on all relevant time scales
- This is the goal of a proposed Fusion Simulation Project (FSP)

Three pilot projects for Fusion Simulation Project (FSP) → Focused integration initiatives

Partnership of OFES & OASCR under SciDAC

- Center for Simulation of Wave Interactions with MHD (SWIM)

  PI: D. Batchelor (ORNL)

  – Integrate RF codes with Extended MHD

- Center for Plasma Edge Simulation (CPES)

  PI: C.-S. Chang (NYU)

  – Brings together studies of kinetic transport in open field line plasmas, turbulence, and macrostability

- Fusion Application for Core-Edge Transport Simulation (FACETS)

  PI: J. Cary (Tech-X Corporation)

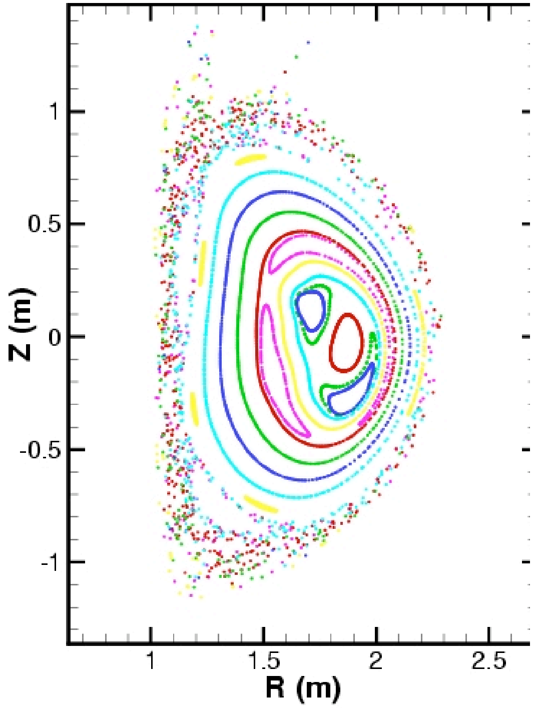
  – Interaction of core transport/turbulence with edge transport turbulence

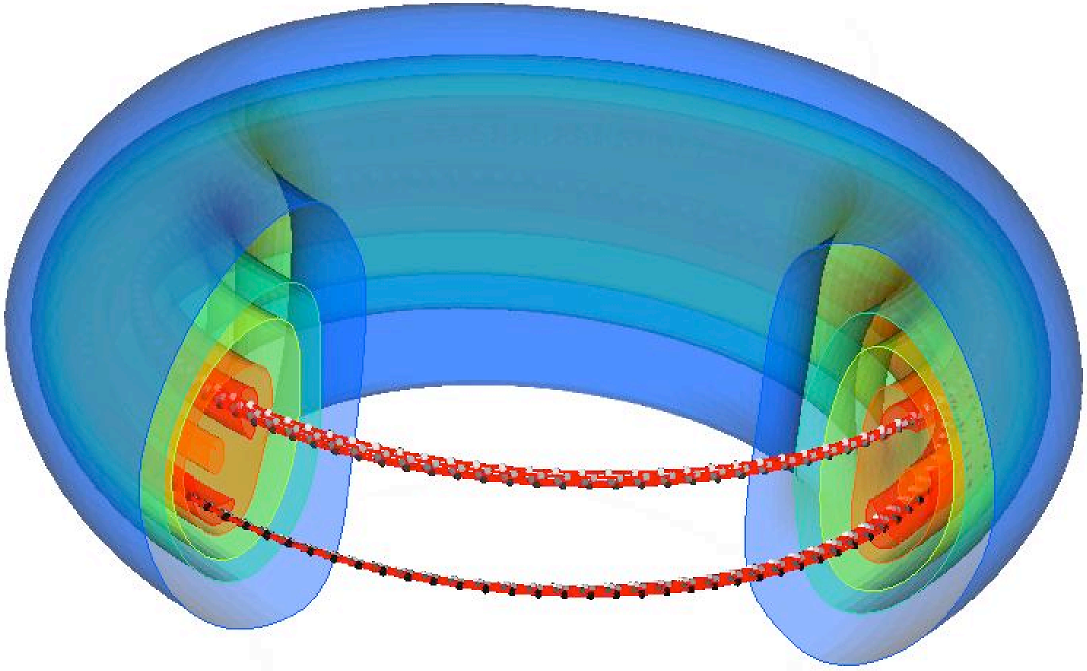
Overview of Fusion Visualization Needs

- Anisotropy important!
  - Particles move faster parallel to fieldlines than perpendicular
- Only the extended MHD codes study topology-changing perturbations
- No one else worries about this (generally)
- First consider extended MHD codes

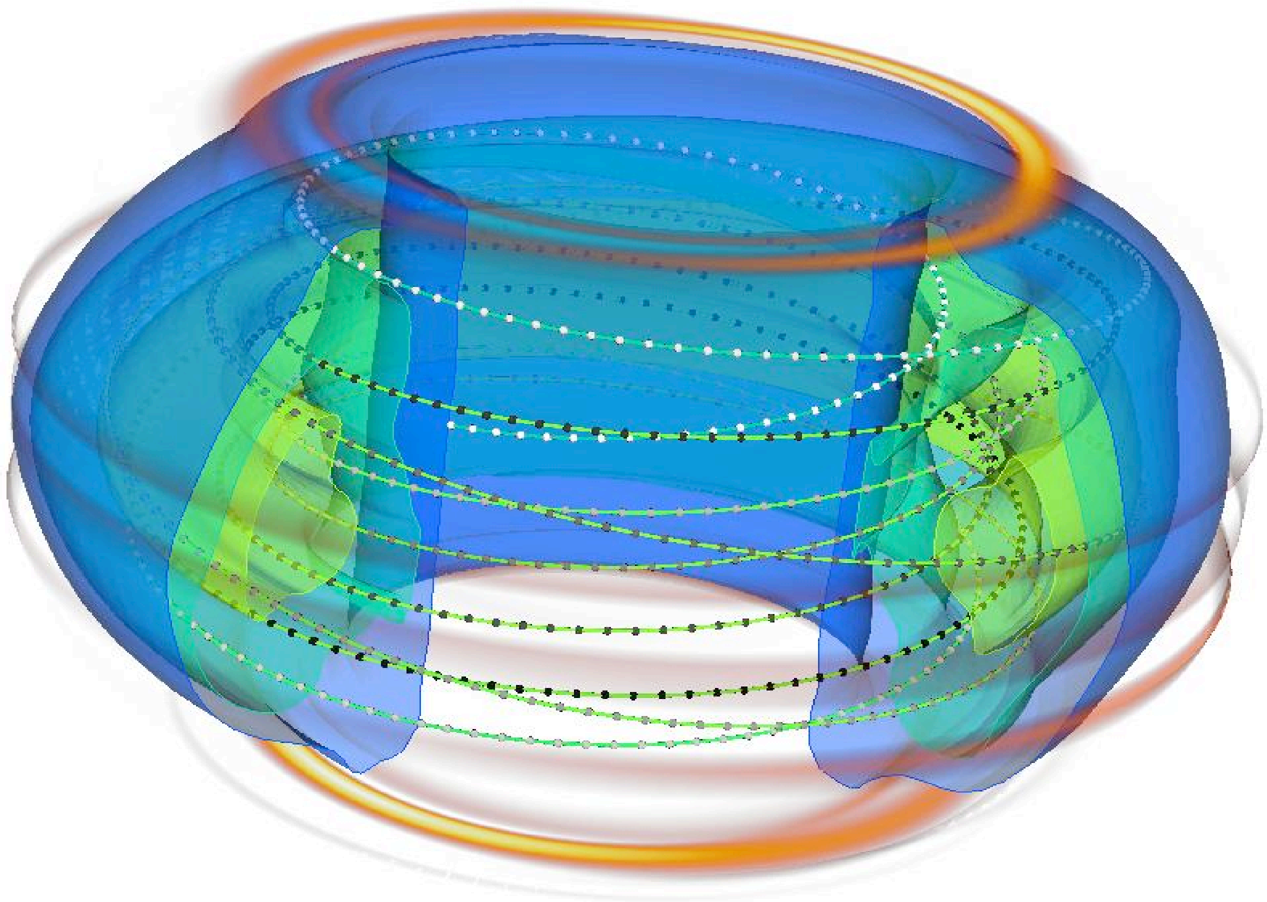
To Illustrate Consider Example of High Beta Disruption

Macroscopic Islands Appear At 2/1 Rational Surfaces

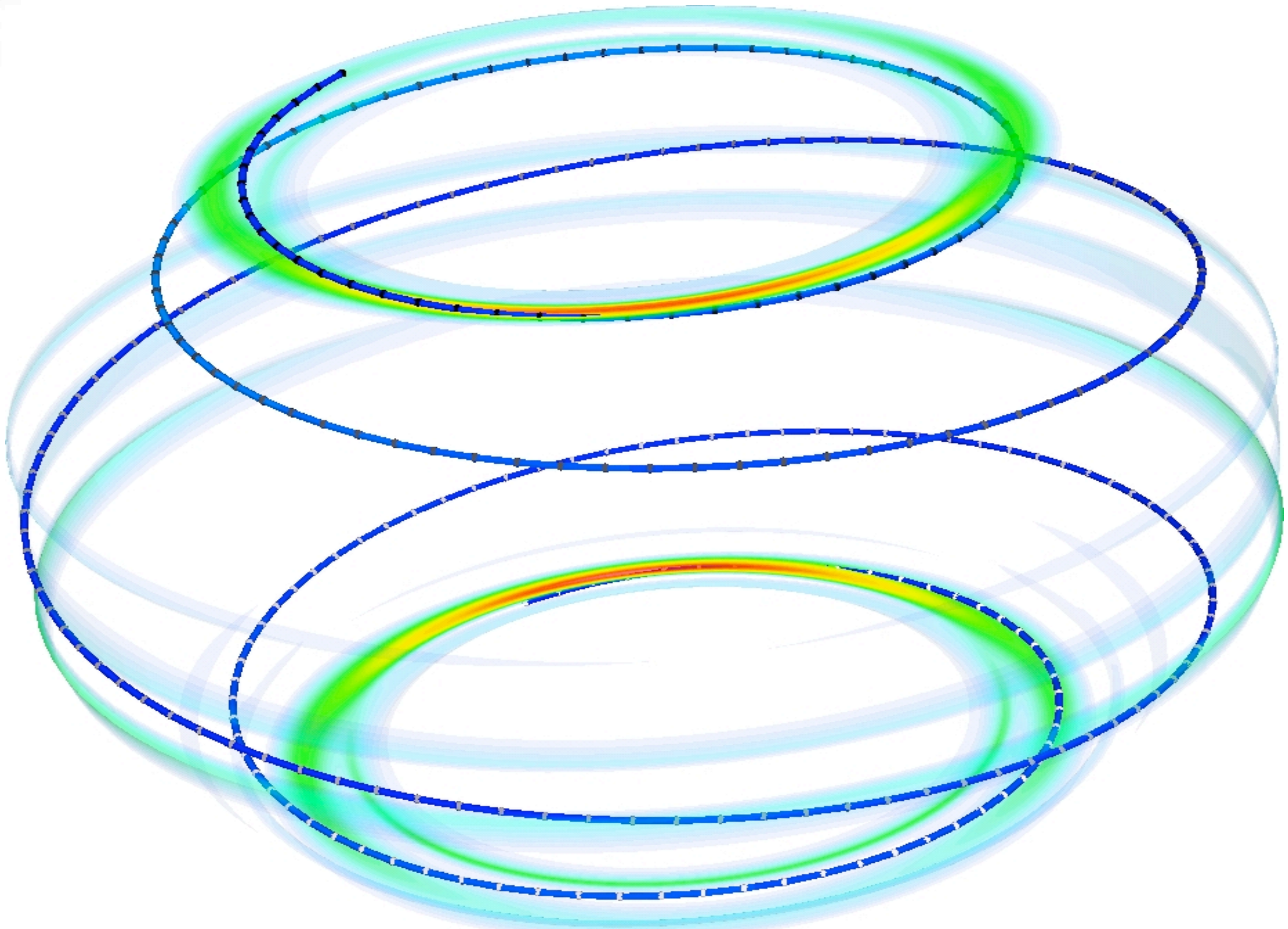




Heat Flux is Localized Poloidally And Toroidally



Localized Areas Of Heat Flux on Top and Bottom Divertors Connected Topologically



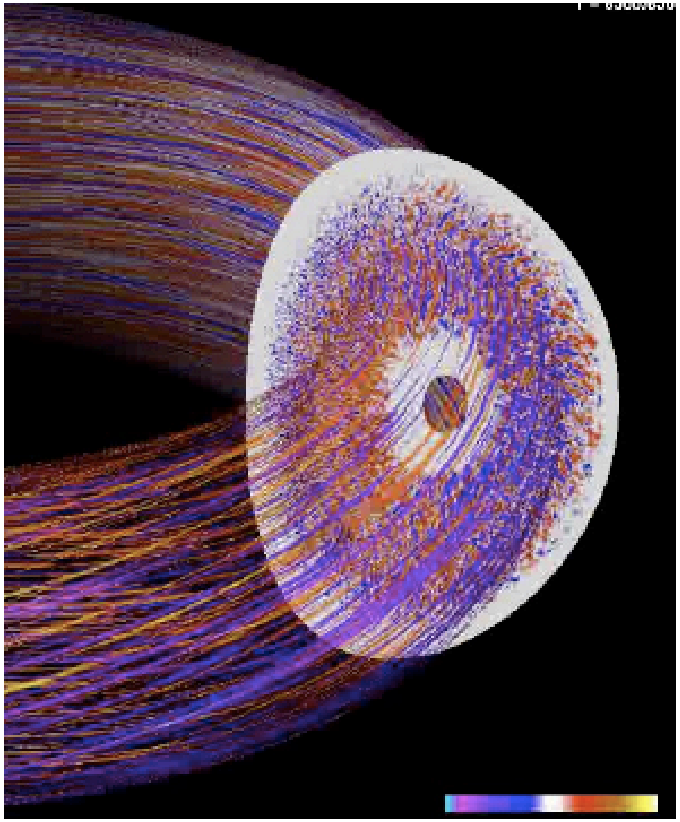
Extended MHD Codes (CEMM/SWIM) Needs

- Rapid detection of islands/topology changes
  - Poincaré plots expensive and difficult to decipher
  - Currently being address as CEMM SAP
  - Also important for stellarator development (S. Hirshman at ORNL)

- How to visualize edge?
  - Fieldlines do not wrap around, but can move and change the physics
  - Increasingly important within SciDAC
  - Similar to needs of CPES/FACETS

Gyrokinetic Turbulence Needs (my take)

- Two kinds of gyrokinetic codes
  - PIC (move macroparticles)
  - Continuum (solve Boltzman eq. like a fluid eq).
- Needs
  - PIC: Lots of particles, which ones to visualize?
    - A.k.a. What's interesting?
  - Both: turbulence analysis
    - Correlations, feature detection, etc. (ref. W. Nevins)
    - Some currently being done, but new ideas possible.



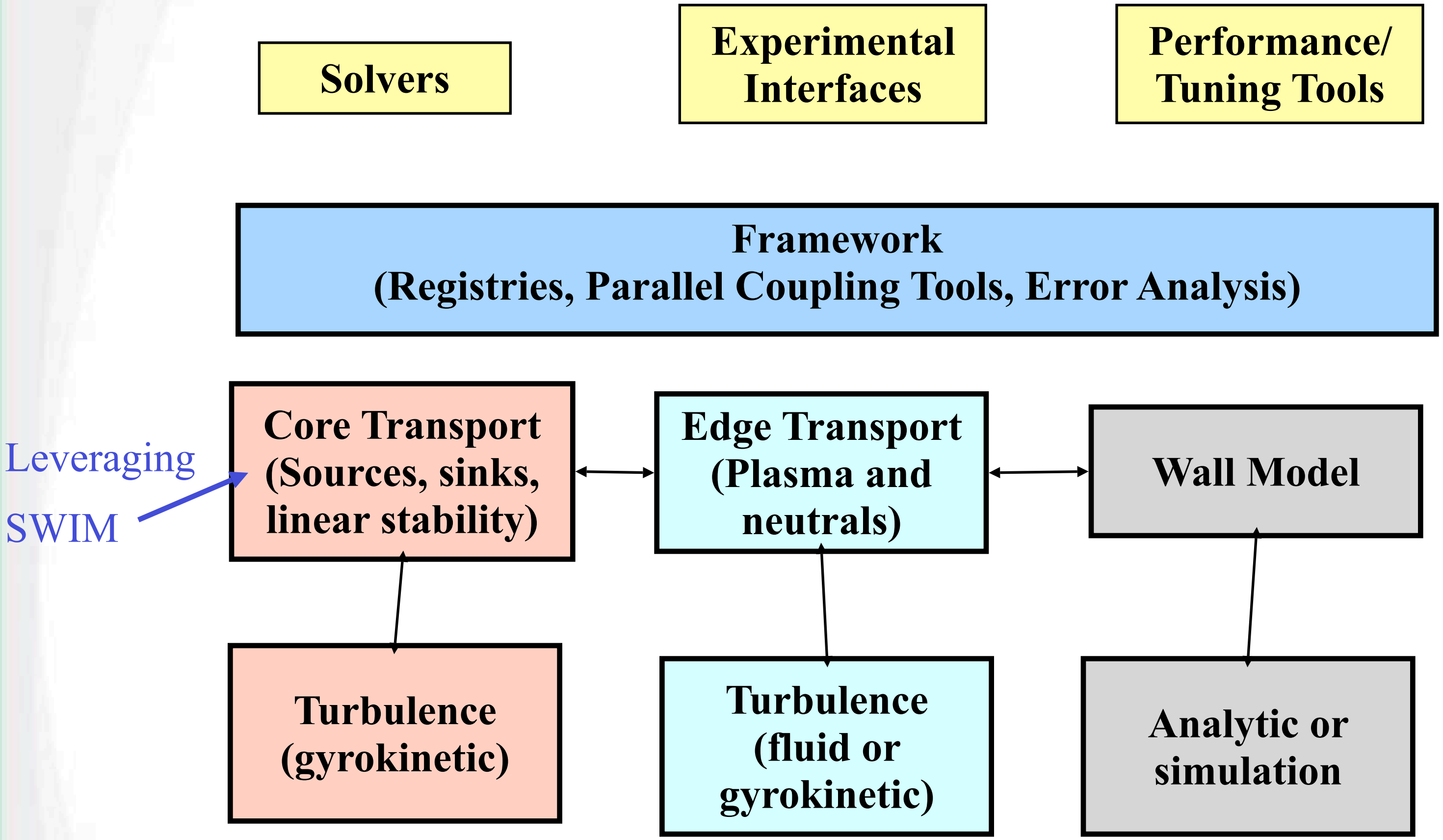
RF SciDAC Needs

- Essence of method is complicated Helmholtz fields solve (find electric field)
- "Bread and butter" visualizations welcome
- Synthetic diagnostics/comparitive vis requested
- …?

Edge Needs

- Most work is in modeling of turbulence at the edge
- Fluid, continuum gyrokinetic, PIC gyrokinetic all used.
- Similar to previously mentioned needs
- Differences
  - Open-versus-closed fieldlines
  - Very narrow region

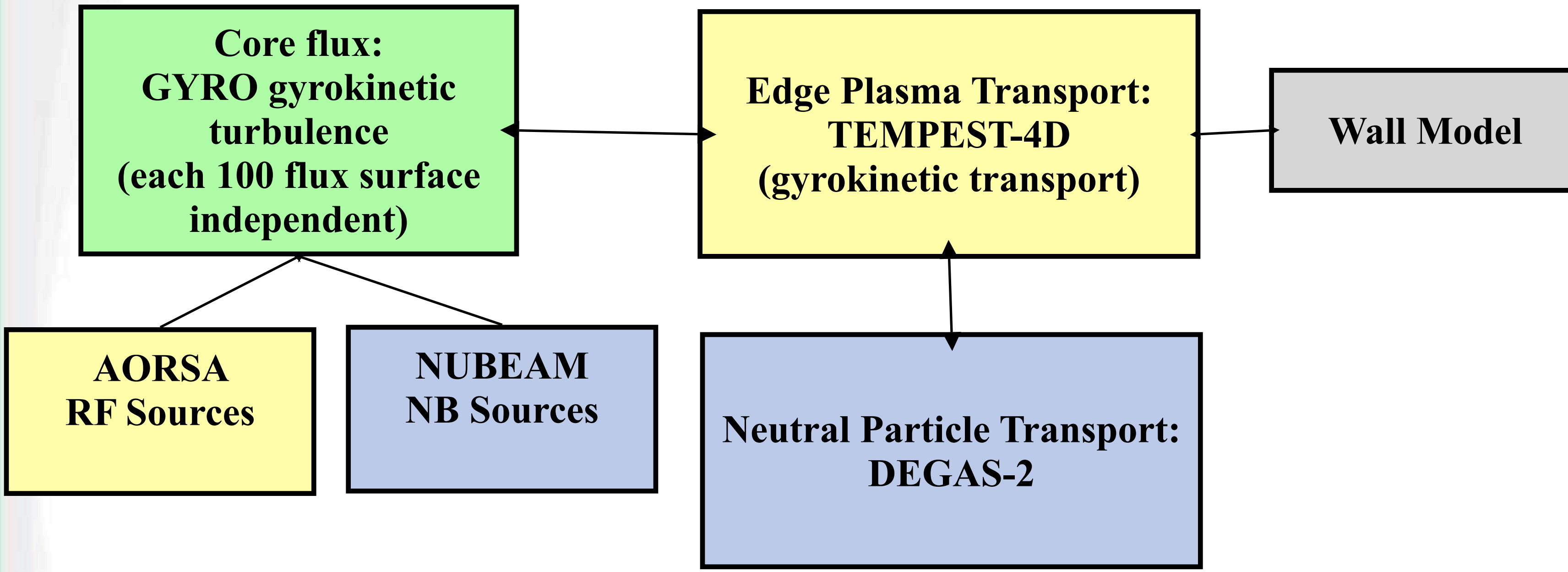
FACETS To Couple Codes With Differing Degrees Of Sophistication and Capability

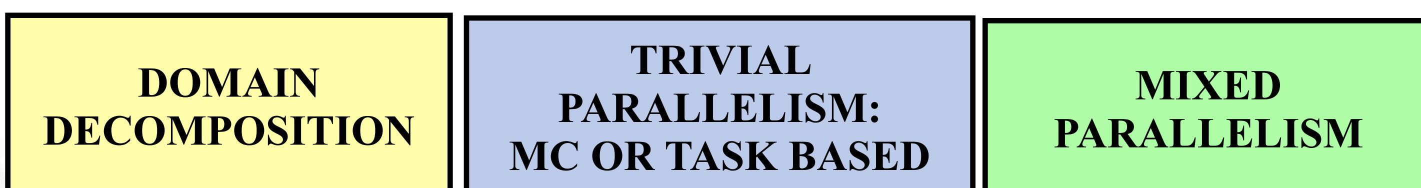


Framework must coordinate
physics, math, and computer science components

Will need to intermingle multiple types of parallelism

- Year 3 target simulation as example:





FSP (FACETS/SWIM/CPES) Needs

- Nonlinear dynamics often difficult to understand
  - Is it real or is it numerics?
  - What does it mean?
- Coupling nonlinear components adds to this difficulty
  - What are the effects of coupling errors?
  - Coupling physics components with different physics capabilities
    => non-experts need to become experts
  - Other?

Conclusions

- There is no “THE” fusion code.

- Traditional SciDACs are mature and successful.
  - Ripe for improved analytics/visualization
  - Parts of similar to computational fluid dynamics
    - MHD: Topology, fluid motion
    - GK: Turbulent flow
  - Particle codes have their own issues
    - Which particles are interesting?
    - Some overlap with accelerator physics

- Fusion is moving towards integration
  - (old problems)++